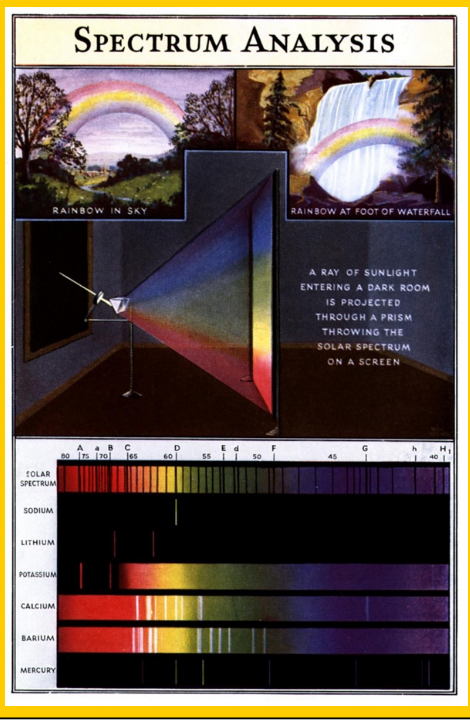
Cosmic Chemistry: Planetary Diversity

Infrared Spectroscopy: Here Comes the Heat

TEACHER GUIDE

BACKGROUND INFORMATION

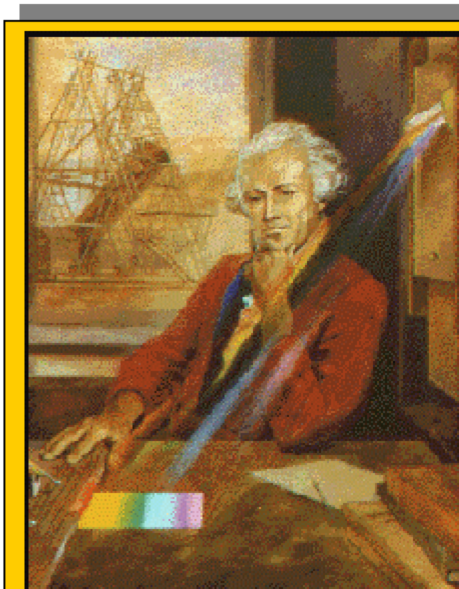


Part I. Introduction to Activity

In this activity students will explore a part of the electromagnetic spectrum that may be new to them in the sense that they cannot experience it visually, in contrast to radiation with wavelengths in the visible part of the spectrum. Your students may have seen infrared heat lamps or infrared heaters, but they probably are not aware of the many beautiful and quantitative scientific applications of infrared radiation in terrestrial laboratories. There are many unrecognized everyday applications as well. One example is remote controls for TV sets, which send commands via a beam of infrared radiation.

Investigations involving infrared radiation have been enormously important over the years in space explorations as well. Since electromagnetic radiation often is the only tangible direct connection with distant objects, space scientists have had to rely on studies of this radiation (the field of spectroscopy) to develop many of their models. Along these lines, you and your students may benefit from reading the student text on Models in Science found in the module, *Cosmic Chemistry: The Sun and the Solar Wind*.

Without question, the primary method for gaining compositional information about distant objects has been to observe their spectral properties. Within the solar system, infrared spectroscopy has proven very useful for establishing such things as planetary atmospheric temperatures and compositions. Clearly, this part of the electromagnetic spectrum has been enormously important in studies that have defined planetary diversity.



NASA/JPL. California Institute of Technology

Sir William Herschel

The first part of the activity is devoted to reproducing a very old experiment conducted by Sir William Herschel in the year 1800. The results of this experiment led to the discovery of infrared radiation. Because of the character of this part of the activity, you may be able to convey a sense of history to the students as they carry out the work. Herschel passed sunlight through a prism, dividing it up into its spectral components, and then he proceeded to measure the "heat" associated with each color in the visible spectrum. To do this he used thermometers placed in each colored beam of light. He blackened thermometer bulbs to increase absorption and reduce reflection. He observed that the temperature increased from the blue to the red part of the spectrum. Most importantly, when he placed a thermometer just beyond the red beam, where there was no visible light, he found that the temperature was even higher. He realized that there must have been an invisible form of light rays beyond the red region. He named them "calorific rays" and they later became known as "infrared" radiation.

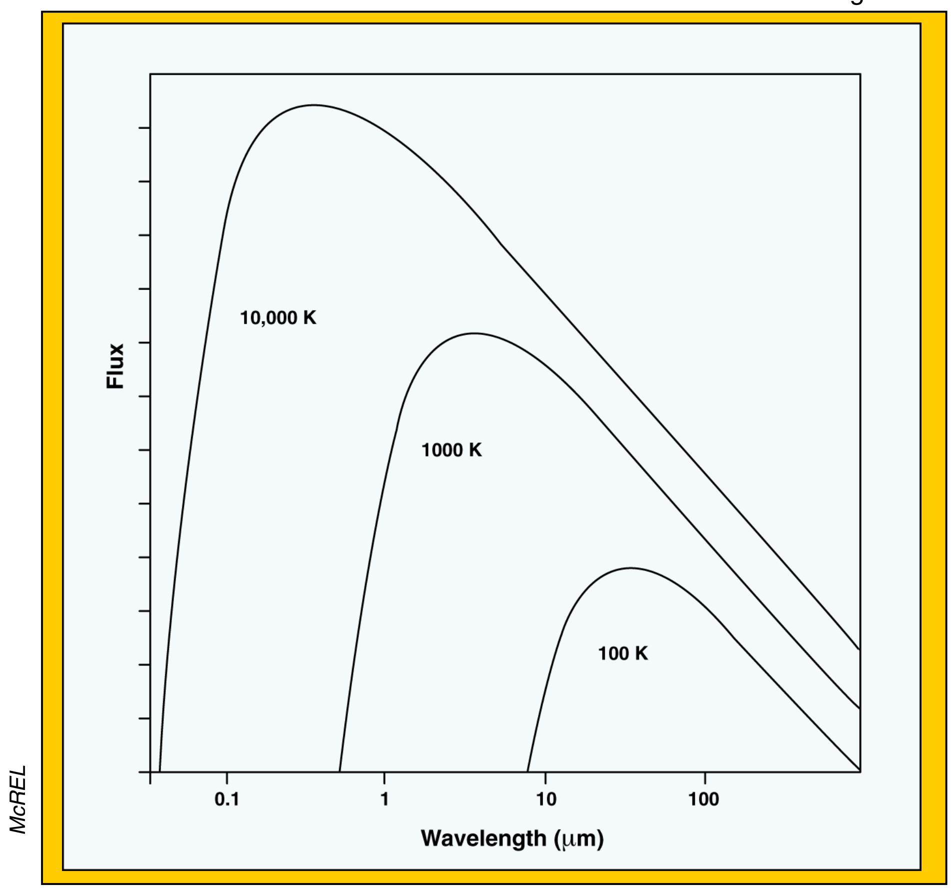
The second part of the activity will introduce students to some of the quantitative aspects of infrared radiation and to infrared spectroscopy. Initially, they will develop a better understanding of the various units used by scientists to characterize electromagnetic radiation, with emphasis on the reciprocal centimeter and the micron. They then will be challenged to imagine what it would be like if they could "see" in the infrared, and they will explore infrared radiation as a means of determining planetary temperatures. Next the students will learn that bonded atoms within molecules usually vibrate in much the same way from one molecule to the next, giving rise to spectral "fingerprints" that can be used for identification purposes. Finally, the students will be given simulated infrared spectra of planetary atmospheres, and they will use their knowledge to identify the atmospheric constituents and the identity of the planets.

Part II. Technical Background

The temperature of any object in the solar system is related very approximately to its thermal infrared signature as follows, where λ_μ is the wavelength of maximum emission in microns and T is the temperature in Kelvins: λ_μ T = a constant.

This expression is derived from studies of the wavelength distribution of the infrared energy radiated by an object at a given temperature. The results of such studies can be represented graphically, as shown in the figure below, for a very wide range of temperatures. (Note that the scales are logarithmic.) Plotted on the ordinate is the flux, F, which is proportional to the number of photons of given wavelength emitted by the object. **In effect, the flux is the brightness of the emissions.**

Figure 1



*These graphs are called Planck function or **blackbody** curves.*

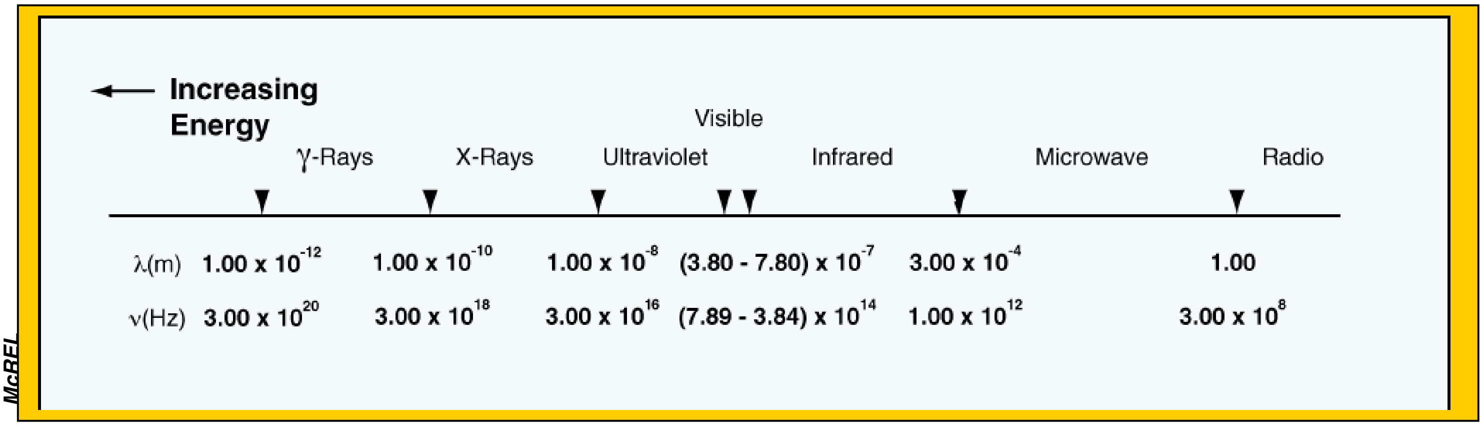
These graphs are called Planck function or **blackbody** curves. For real objects, the wavelength at the maximum in the curve (λ_μ) may be used to estimate the object's temperature by applying the formula given above. For Mars and Pluto the maxima are from about 13 μm to 100 μm, respectively. Using the above equation, the approximate temperatures of 220 K and 30 K, respectively, for these two planets can be calculated . (See Alternate Strategy Tips p. 5 of the Teacher Guide.)

Sometimes it is convenient to describe electromagnetic radiation in terms of its frequency, ν (nu), instead of its wavelength, although the two are related as follows, where c is the velocity of light: $\nu = \frac{c}{\lambda}$.

The frequency is the number of wave crests that cycle by a stationary observer in one second. The frequency therefore tells us how fast the radiation oscillates in its up and down motion.

We also make note of the energy of electromagnetic radiation, which is proportional to the frequency, as expressed through the equation $E = h\nu$, where h is Planck's constant. Radiation having a high frequency (or short wavelength) is very energetic and vice versa. Some of these relations are summarized in the figure below.

Figure 2



McBEL

When dealing with infrared radiation yet another unit of "energy" often is used, since electromagnetic energy, E, can be written as: $E = h\nu = h\frac{c}{\lambda}$.

Energy clearly is proportional to the reciprocal of λ, and it is common simply to express "energy" in terms of reciprocal wavelength, or wave number, cm^{-1}. Strictly speaking a wave number is not an energy unit, but usually it is treated as such. Spectroscopists certainly must be conversant with a variety of units, and for infrared studies it is especially important to be able to convert microns to wave numbers and vice versa.

The easiest way to convert microns to wavenumbers is to first divide μm by 10^4 to convert μm to cm. Then you can simply take the reciprocal of cm to obtain cm^{-1}. For example, we see that 100 $\mu m = 10^{-2}$ cm, giving 100 cm^{-1} when the reciprocal is taken. Likewise we can see that 1 $\mu m = 10^{-4}$ cm, giving 10,000 cm^{-1}. The infrared region of the electromagnetic spectrum lies roughly between 12,500 cm^{-1} (0.8 μm) and 10 cm^{-1} (1000 μm).

As is the case with radiation in the visible part of the spectrum (see the Genesis education module, *The Sun and Solar Wind*), molecules can absorb infrared rays as well as emit them. That is to say, a molecule struck by a beam of infrared radiation may absorb certain frequencies and provide an absorption spectrum. Such spectra, which are obtained with an instrument called an infrared spectrometer, provide a wealth of information about the molecule. Obtaining these spectra requires the use of "high-resolution" instruments, as opposed to the "low-resolution" instruments employed for determining the temperature of an object. An infrared spectrometer is a device that permits one to inspect sections of the infrared spectrum under high-resolution conditions-it is not used to determine temperature. Rather it is used to determine the composition of materials.

Infrared spectra usually are presented in graphical form, with the intensity of absorbance on the ordinate and the "energy" (expressed in cm^{-1}) of the radiation on the abscissa. A spectrum of the water molecule (H_2O) in the gas phase is shown in figure 3a and deuterium oxide (D_2O) in figure 3b below, where the downward pointing spikes indicate absorption of radiation.

Figure 3a

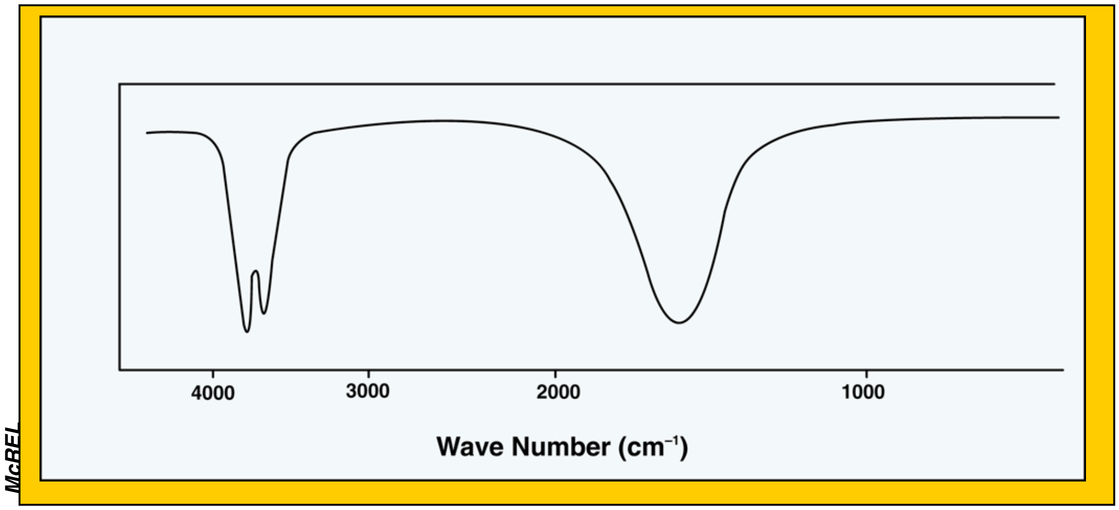
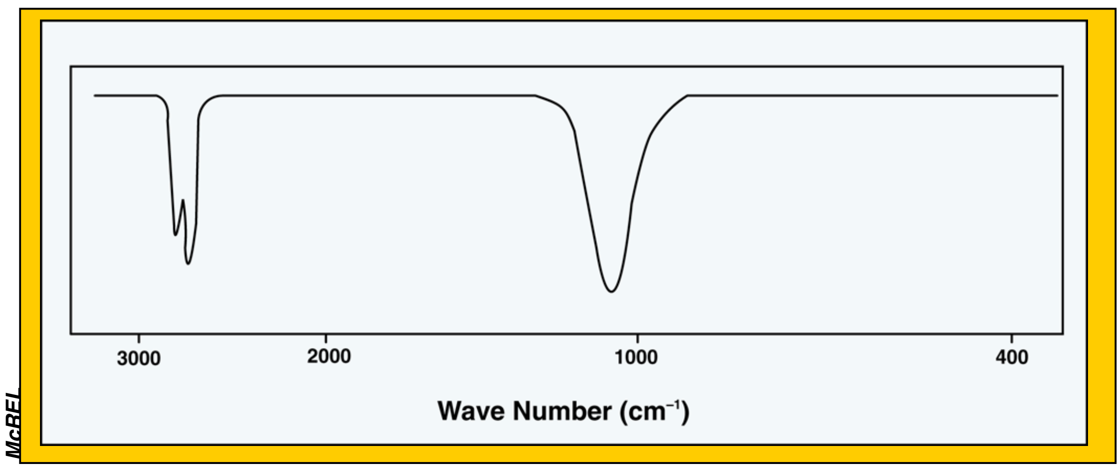


Figure 3b



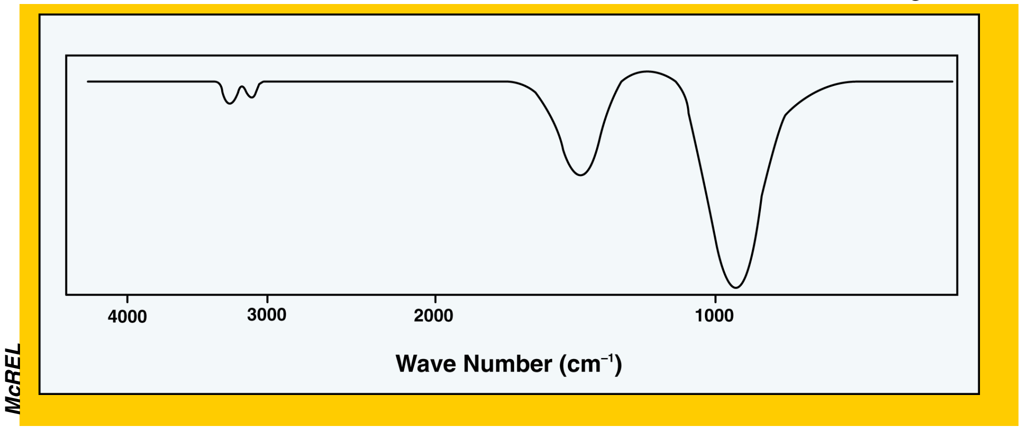
We see that water vapor absorbs infrared radiation strongly at 3756, 3657, and 1595 cm^{-1}. This pattern is characteristic of water and can be used to identify water in a sample. Other molecules have their own unique patterns; consequently, infrared absorption spectroscopy is an incredibly important tool for identifying the components of an unidentified substance.

We note also that when infrared radiation is absorbed by a molecule, the molecule's vibrations are changed. Hence, infrared spectroscopy sometimes is called vibrational spectroscopy, and as a very rough approximation, molecules may be regarded as solid balls (atoms) connected by springs (bonds). Since vibrations are affected by the mass of the vibrating objects, an infrared spectrum may be altered through substitution of one isotope for another. This is most evident with hydrogen, and is shown in Figure 3b, the spectrum of heavy water, D_2O.

One clearly can see that there are the same number absorptions as those for normal water, but that the energies of the absorptions are lower. This reflects the vibrational changes wrought by doubling the mass of the atoms attached to the oxygen atom. In general the heavier the two atoms involved in a vibration, the lower in energy (cm^{-1}) will be the characteristic vibration. Make note of the fact that infrared absorptions are properties of molecules such as water and ammonia. Individual atoms such as He or N do not absorb infrared radiation as do molecules. It also is the case that molecules such as N_2 do not absorb radiation in the region 400-4000 cm^{-1} where we find the infrared signatures of molecules like water and methane. On the other hand, molecules such as HCl do exhibit characteristic absorptions in this region.

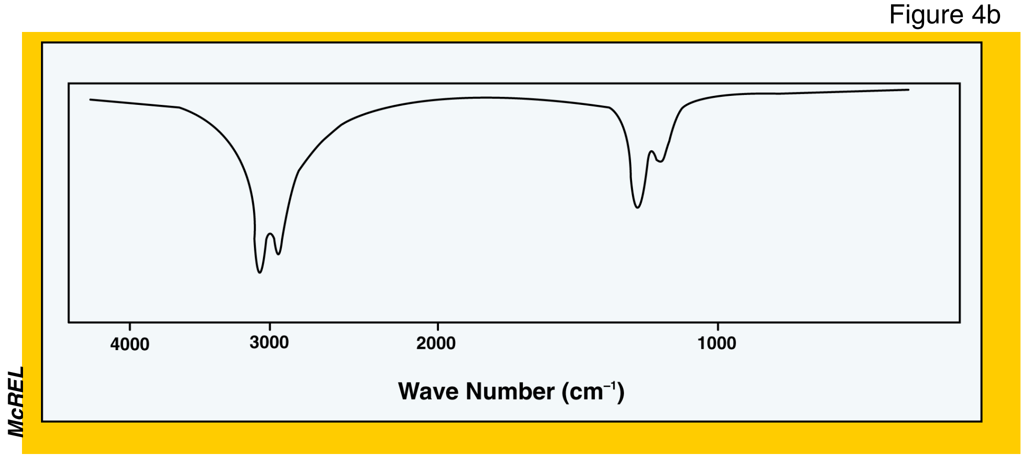
Shown in the figures below are the infrared spectra of the ammonia (Figure 4a) and methane molecules (Figure 4b). These molecules, along with other well-known chemical materials such as carbon dioxide, are found as primary constituents in the atmospheres of several of the planets.

Figure 4a



Ammonia infrared spectrum.

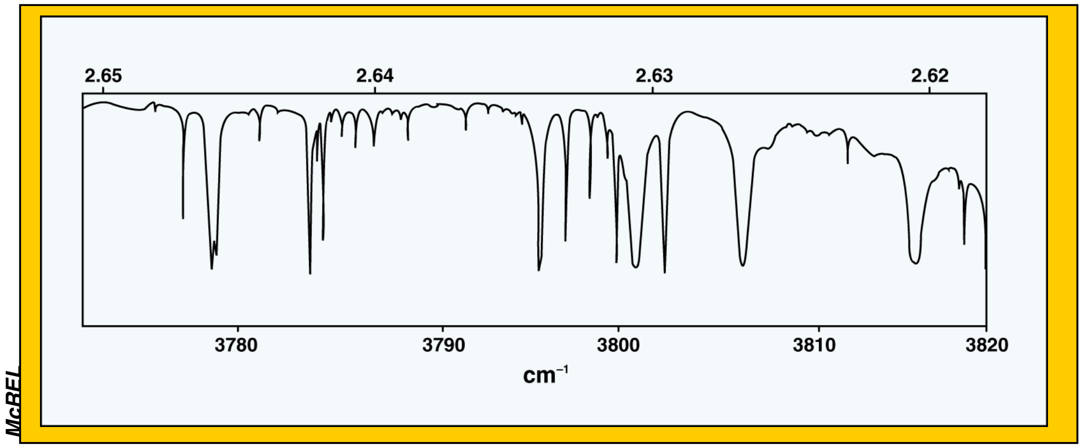
Figure 4b



Methane infrared spectrum.

Studies of infrared absorption by a distant object may provide valuable clues about the composition of the object. For example, if a planetary surface emits infrared radiation thermally, some of this emitted radiation may be absorbed by materials in the planet's atmosphere. Through a study of the planet's infrared emission properties under high-resolution conditions, it becomes possible to identify the components in the planet’s atmosphere through their infrared signatures. A detailed, very high resolution spectrum of a planetary atmosphere is shown in the figure below.

Figure 5



Clearly, there are many components of the moon's atmosphere that absorb infrared radiation.

Kitt Peak National Observatory near Tucson, AZ

These kinds of experimental studies are very difficult to make using terrestrial infrared telescopes because Earth's own atmosphere is loaded with water and other molecules that strongly absorb incoming radiation, making the atmosphere opaque. In fact, there are only a frustratingly few wavelength regions where incoming infrared radiation can be studied without interference from atmospheric gases. For example, there are localized "windows' at 4.7-5.2, 7-13, and 20 µm, among others. This is why it is common to locate observatories high on mountain tops, where they are above at least some of the Earth's atmosphere. Better yet, of course, is to send infrared instruments into space where the atmospheric interferences are avoided altogether.

NATIONAL SCIENCE STANDARDS ADDRESSED

Grades 5-8

Science As Inquiry

Abilities Necessary to do scientific inquiry
Understandings about scientific inquiry

Physical Science

Properties and changes of properties in matter
Motions and forces
Transfer of energy
Interactions of matter and energy

Science and Technology

Understandings about science and technology

History and Nature of Science

Science as a human endeavor
Nature of science and scientific knowledge
History of science and historical perspectives

Alternate Strategy Tips

If your students lack the mathematical background to complete Parts 2-5 of this activity, you may want to consider completing Parts 2-5 as a class. You could ask inquiry questions similar to those included in the remainder of the Student Activity, "Infrared Spectroscopy: Here Comes the Heat."

You also could use transparencies or handouts of the figures and tables included in the Student Activity in the classroom discussion.

Another option is to have students complete only Part 1 of the Student Activity.

Note that Part 1 of the Student Activity is separated from Parts 2-5.

Grades 9-12

Science As Inquiry

Abilities Necessary to do scientific inquiry
Understandings about scientific inquiry

Earth and Space Science

The origins and the evolution of the universe
Energy in the Earth system

Physical Science

Properties and changes of properties in matter
Motions and forces
Transfer of energy
Interactions of matter and energy

Science and Technology

Understandings about science and technology

History and Nature of Science

Science as a human endeavor
Nature of science and scientific knowledge
History of science and historical perspectives

(View a full text of the National Science Education Standards.)

MATERIALS

For each student:

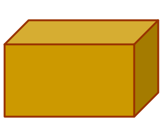
- Copy of Student Handout, "Figures Relating to "Here Comes the Heat" Activity
- Copy of Student Activity, "Here Comes the Heat"
- Copy of Student Text, "Infrared Radiation: Here Comes the Heat"
- Copy of Reporting/Data Sheet for "Here Comes the Heat"
- Copy of Graph of Thermal Infrared Flux *vs.* Wavelength

In addition, for Part 1:

For each team:

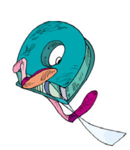
An inexpensive equilateral glass prism, such as those available from Frey Scientific.
Three or four inexpensive alcohol thermometers that have had their bulbs blackened. (Mask off the thermometers and spray the bulbs with flat black paint.)
Optional materials: probeware may be used in place of thermometers.

Other materials as required by the team design. These likely will include a



box (the size that reams of copier paper come in),

a piece of white paper,



and scotch tape.

Alternate Strategy Tips

Hints that you may offer, depending upon the ages and backgrounds of your students, include:

- The necessity for a "control" thermometer for measuring temperature in the shade (for comparison purposes).
- What measures must be taken to minimize the effect of the sun's movement across the sky.
- The infrared must be observed just outside of the visible red part of the spectrum.
- It probably will be sufficient to observe temperatures only in the blue, yellow, and infrared regions.

If you want to help them even more, suggest that they obtain a large box (of the type that copier paper is delivered in) and do the following:

- Completely remove the top of the box.
- Place white paper in the bottom of the box.
- Place the prism in a position such that a good spectrum is cast on the white paper (it may be necessary to tilt the box in order to receive the sun's rays).
- Once a good arrangement of box and prism is obtained, tape the prism in place; record the maximum temperatures that are developed in each color after a few minutes when equilibrium is reached.

The experiment will be optimized if the prism is around 0.3 m from the "screen." A set of detailed instructions for conducting the experiment as described above can be found on the Internet at the location specified in the reference section. Other experimental setups can be found in guides for science fair projects (see reference list for this module).

PROCEDURE

1. Read the technical background in teacher's guide. Decide the most appropriate way to introduce this material with your students.
2. Before class, make copies of the following:
   - Student Handout, "Figures Relating to "Here Comes the Heat" Activity
   - Student Activity, "Here Comes the Heat"
   - Student Text, "Infrared Radiation"
   - Reporting/ Data Sheets for "Here Comes the Heat"
3. Distribute copies of the student activity, student text, and reporting/data sheets.

Alternate Strategy Tip
The students must understand the meaning of the blackbody emission curves, as discussed in the teacher's guide. Make sure they realize that a body at 275 K would appear much brighter than would an object having a temperature of 175 K, since the flux in the former case is much higher than in the latter case. The shape of the curve in Figure 1 of this teacher's guide indicates that there is a distribution of wavelengths emitted by an object at a given temperature. For example, an object having a temperature of 275 K does emit at, say, 5 microns, but its brightness at that wavelength is only about half that if it were observed at 10 microns.

PART 1

4. For Part 1, organize the class into teams of 4-5 students per team. Read information on William Herschel from teacher's guide. You may want to have the students read or discuss excerpts from the technical background.

   Have students answer the following questions:
   - Why do you think Herschel placed the thermometer outside of the visible spectrum?
   - What would Herschel's null hypothesis have been?

   Direct each team to devise an experimental set-up that can be used for duplicating their experiment. Tell students that you will provide prisms and thermometers at the appropriate time.

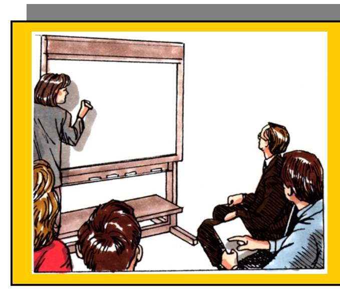
   Each team should submit a written description, complete with diagrams, of the experimental set-up that they will use.

   Post the descriptions in locations around the room for all students to read.

5. After the students have devised and submitted an experimental procedure, but before the students actually conduct the experiment, bring the class together for a discussion of the various procedures that have been proposed. At this point it would be appropriate to bring other factors or questions up for discussion, such as:
   a) What effect will time of day have on the experiment?
   b) What effect will the distance of the prism from the thermometers have on the experiment? (The further away the prism is from the paper screen, the more spread out the projected spectrum will be, and the smaller the temperature increases will be, since the thermometers will intercept less energy.)
   c) Why are the thermometer bulbs painted black?
   d) What were the controls in this experiment?

6. Give each team a chance to modify their proposed procedure, if necessary, and then tell them to conduct the experiment that they have designed. Ask them to prepare a report on their findings and submit it to you. As part of the report, they should devise a table that gives the values of the measured temperatures in each color of light and a conclusion for their experiment. Post all of the tables around the room so that the results can be compared.

7. After the students have completed their work, engage them in a discussion organized around questions like the following:
   a) Is infrared radiation harmful to one's eyes?
   b) How does infrared radiation differ from radio waves?
   c) Can infrared radiation be reflected?
   d) Can infrared radiation be diffracted?
   e) Can infrared radiation be absorbed?
   f) How do humans detect infrared radiation?



PARTS 2-5

> **Alternate Strategy Tip**
> As an added touch you might want to consider designing, producing, and giving to each student a certificate from the Hershel School of Infrared Studies that certifies that they have successfully completed the assigned activities.

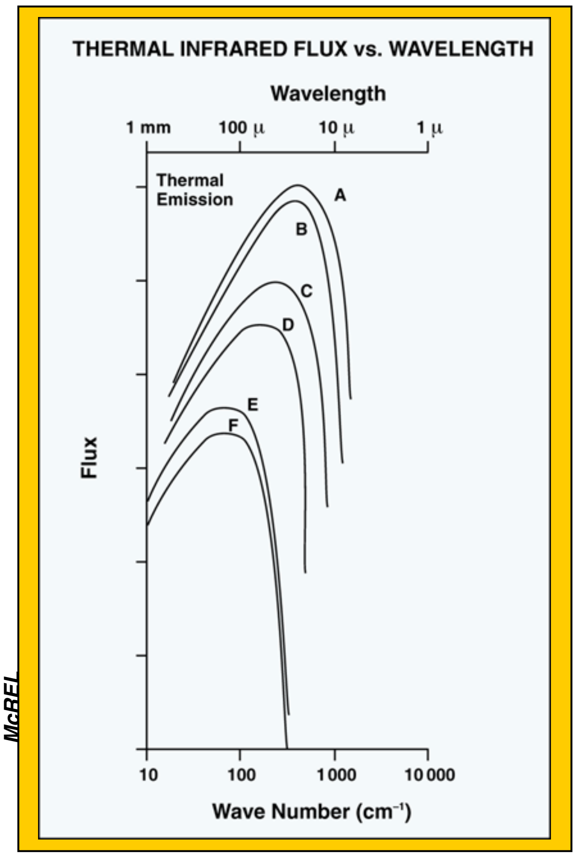
8. Set the scene for the Student Activity "Infrared Spectroscopy: Here Comes the Heat," by telling the students that they now are enrolled in the Herschel School of Infrared Studies and that you are their professor, Dr. Sweets Herschey. As the students complete the various steps of the Activity, you will monitor their progress and give them approval to move from one step to the next based on their performance. Of course, you should exercise your judgment as to whether they have satisfactorily completed a given assignment.

9. Part 2 is self-explanatory and requires only that you review the information given in the student text and teacher's guide on the relation among microns, nanometers, and reciprocal centimeters. You may want to provide some examples and answers.

10. Part 3 is reasonably self-explanatory, but you may want to emphasize that the students are to imagine that they can see ONLY that radiation having a wavelength of about 10 microns (IR region). Encourage them to think about the **blackbody** emission curves before they answer the questions, and make sure they understand that real objects can be roughly modeled by assuming they are ideal black bodies. It also is VERY important for the students to be able to convert temperatures of everyday objects to absolute temperature (Kelvin) since the curves are given in Kelvins. You might want to emphasize this if the students are not used to making these conversions already.

    If necessary, give them the formulas: °C = 5/9 (°F-32) and K = 273.15 + °C.

11. Part 4 requires that you give each student a copy of a Graph of Thermal Infrared Flux *vs.* Wavelength for several planets. Emphasize from the Student Text the equation: $\lambda_{\mu}T =$ constant**,** and how this equation can be used to estimate the relative ordering of temperatures of objects from a study of their emission flux as a function of wavelength. The students will need to read other sections of this module to estimate the average temperature of Mercury before they can complete the third task.



12. Part 5 is self-explanatory and it only involves the use of simulated, highly simplified infrared spectra found on the reporting/data sheet. Real astronomical data generally are too complicated for students at this level to understand and interpret. Hence, the simulated spectra. This exercise will give students the idea of how infrared astronomy can be useful for determining atmospheric compositions from a distance. In order for students to complete this part of the activity, it is necessary for them to use known planetary atmospheric compositional data. This information is available in Tables 5 and 6 of the Student Activity, "Are We Related?"

13. During the follow-up session for Part 2 of this activity, ask questions similar to the following:
    a) If Mars has a temperature that varies from 150 to 275 K, over what wavelength range would it emit most of its energy?
    b) An optical pyrometer is a device for measuring the temperature of objects only by their visible color. Glowing red objects are cooler than white-hot objects. Why can a pyrometer be used only to measure the temperature of objects that are hotter than about 900 °C.
    c) Why can it be said, "There are cool objects in space that are extremely prominent at long wavelengths and yet totally undetected at shorter wavelengths?"

d) The Earth's atmosphere is warm, so it possesses thermal emission characteristics of a body having a temperature of about 270 K. At what wavelength would the Earth's atmospheric thermal emission be most detrimental to terrestrial infrared observations of the planets?

e) The detector of an infrared telescope is the heart of the instrument, since it actually detects incoming photons of radiation. Recent astronomical infrared telescopes have involved detectors that are cooled to liquid helium temperature, which is only slightly above absolute zero. Why is it necessary to cool the detectors of infrared telescopes and their surroundings to as low a temperature as possible?

f) The sun can be regarded as a mass of hot, ionized gas. See information in the Genesis module, *The Sun and Solar Wind*. Explain the statement, "The infrared wavelength we select determines how deeply into the sun we can observe."

g) If the atmosphere of a planet had mostly carbon disulfide, how would the high-resolution infrared spectrum compare to that of a planet having mostly carbon dioxide in its atmosphere?

h) If an infrared telescope detected silicates, which are components of many soils, in the atmosphere of a planet, what would this tell us about climactic conditions on the planet?

i) Some mammals are largely nocturnal, spending most of their awake-time cruising around at night. Do you think these animals are able to see better at night than do humans? Do they use infrared radiation to see at night? Or do they simply have higher sensitivity to visible light than do humans, making it possible for them to see much lower levels of light than we can.

j) What animals are able to detect the infrared radiation given off by other animals?

k) Are there units, other than microns or nm, in which wavelengths of infrared radiation might be reported?

Alternate Strategy Tip

In the equation, $\lambda_{\mu}T =$ a constant, the constant takes one of two values, depending on the exact way in which the graph is presented. The details are beyond the level of this activity, but for your information, the way in which most physicists use the equation requires a value of 2898 µK. The other value for the constant is 3670 µK. Your students will derive a value based on the average temperature of where you are located on the Earth and the position of the maximum in the curve for Earth. Their numbers probably will not be very close to either of these values, because of several factors—including the fact that planets are not perfect examples of black bodies. It also is difficult to read highly accurate values of wavelength from the graph, as well as to determine the exact maximum on the curve. It is not the point of this activity for them to be quantitative in their conclusions. More important is the process.